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Damage precursor detection for structures subjected to rotational base vibration

Ed Habtour [a], Daniel P. Cole [a], Samuel C. Stanton [b], Raman Sridharan [c], Abhijit Dasgupta [c]

[a] U. S. Army Research Laboratory, Vehicle Technology Directorate, APG, MD 21005, USA
[b] U. S. Army Research Office, Mechanical Science, APG, MD 21005, USA
[c] University of Maryland, Center for Advanced Life Cycle Engineering, College Park, MD 20742, USA

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ABSTRACT

This paper presents a nonlinear dynamic methodology for monitoring precursors of fatigue damage in metallic structures under variable rotational base excitation. The methodology accounts for important nonlinearities due to the complex loading generated by variable rotation and structural degradation. The sources of the nonlinearities include: structural stiffening due to gyroscopic motion and high-response amplitude at the fundamental mode, softening due to inertial forces and gyroscopic loads, and localized microscopic material damage and micro-plasticity. The loading intensity and number of vibration cycles increase the influence of these effects. The change in the dynamic response due to fatigue damage accumulation is experimentally investigated by exciting a cantilever beam at variable rotational base motions. The observed fatigue evolution in the material microstructure at regions of large stresses (and the resulting progressive structural softening) is tracked by quantifying the growth in the tip response, the change in the fundamental natural frequency of the beam and the skewedness of the stepped-sine response curve. Previous understanding of the structural dynamic behavior is necessary to ascertain the damage precursor location and evolution. Nanoindentation studies near the beam clamped boundary are conducted to confirm the gradual progression in the local mechanical properties as a function of loading cycles, and microstructural studies are conducted to obtain qualitative preliminary insights into the microstructure evolution. This study demonstrates that careful monitoring of the nonlinearities in the structural dynamic response can be a sensitive parameter for detection of damage precursors.

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1. Introduction

There are many engineering systems that experience variable rotational base excitations, such as flexible robotics components, heavy electronics components, and unmanned ground and aerial systems [1,2]. Many of these systems may experience harsh dynamic loads during their life cycles [3,4]. Mechanical structures under variable rotational base excitations may experience complex dynamic effects, such as gyroscopic stiffening and softening, nonlinear geometric stiffening, and nonlinear inertial softening [1,2]. Modeling and measuring the dynamic response can be complicated when the material properties evolve due to fatigue damage accumulation. In this study, we focus on the growth of early precursors to such fatigue degradation. *Fatigue damage precursor* is defined as any observable early degradation of the material microstructural properties prior to crack initiation [5]. Precursors to fatigue crack development may involve, but are not restricted to, changes in the microstructure, chemical composition, electrical signal, acoustic response, or thermal signature of a structure.

This study demonstrates that the dynamic response of a structure due to rotational vibration excitation can serve as a particularly sensitive precursor for fatigue degradation evolution. To facilitate this demonstration, an analytical nonlinear dynamic model is provided, which includes multiple sources of nonlinearities due to the variable harmonic rotational base excitation and the high amplitude response. The presented methodology shows that it is possible to capture fatigue damage precursors by simply tracking the change in the nonlinear stiffness term in the equation of motion. The nonlinear equation of motion is then updated accordingly to capture the local microstructural evolution by adjusting the nonlinear structural stiffness term. The global nonlinear vibration-based method uses the nonlinear structural updates from the experiments to estimate the beam tip response and number of fatigue cycles. The technique can be used to assess the structural durability of mechanical systems when they are

E-mail address: ed.m.habtour.civ@mail.mil (E. Habtour).

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exposed to complex vibratory loading using conventional sensors, such as accelerometers. Therefore, it is possible to utilize the proposed methodology to detect fatigue damage precursors in mechanical components using current health monitoring systems (SHM) by including the nonlinear terms in their detection codes; this can be done without physical replacement or the addition of sensors.

Multiple studies have been devoted to nonlinear dynamics and vibrations of beams because of their importance in many engineering applications. One of the most cited studies in nonlinear dynamics is the effort presented by Hodges and Dowell [6], where they developed the equations of motion for a rotor blade idealized as a beam, using Hamilton's principle. They maintained the cubic nonlinear terms and included the effect of warping. Partial-differential equations for the motion of nonlinear inextensional and extensional beams were developed for planar and nonplanar base excitation, where the geometric and inertial nonlinearities were included [7–12].

Beam models were improved to idealize more complex structures such as antenna and radar structures, aircraft wings, and wind turbines. Some of these modeling improvements included stepped beams and L-shape beams with tip masses [13–17].

Several researchers have investigated the dynamics of rotating linear and nonlinear flexible beams and flexible hub-beams (rotor-blades) with tip mass [18–20]. These dynamic models were developed in a consistent manner through the formulation of energy expressions and application of Hamilton's principle. The models included dynamic stiffening and inertial softening [21]. Hodges [22] developed nonlinear dynamic models for composite beams and blades exposed to constant base rotational velocity. Radially rotating uniform linear beams under constant and non-constant angular velocity have also been investigated [23–25]. However, most of the research performed in studying the vibrational behavior of radially rotating beams has focused on constant spin velocity with various combinations of free, clamped, and simply-supported boundaries [17,20,26].

Absent in the structural dynamics and structural health monitoring literature is a comprehensive theoretical and experimental study of the response of structures exposed to vibrational rotational base excitation that includes all of the following sources of nonlinearities: (1) geometric stiffening, (2) inertial effect, (3) gyroscopic stiffening and softening, (4) higher order nonlinear gyroscopic stiffening, and (5) coupling between the rotational excitation (primary motion) and local displacement (secondary motion). These nonlinearities may potentially become significant when modeling fast and flexible robot manipulators, robotic arms, and adaptive structures under nonlinear oscillatory motion. High cycle vibrations in these structures may lead to fatigue, instability, and loss of position accuracy. The problem can be exacerbated in structures where the system dynamic response progressively changes as the material continues to degrade due to the accumulation of cyclic fatigue damage.

In the current investigation, we exploit the sensitivity of the geometric stiffness to the accumulation of fatigue damage by modifying the nonlinear equation of motion to account for degradation in the local stiffness at high-stress sites. The approach appears to be a promising metric for providing sensitive and robust structural health monitoring to predict fatigue damage precursor in metallic structures. The study shows that the nonlinear vibration-based measurement techniques sense the development of fatigue damage precursors prior to crack initiation. The fatigue-induced structural softening of the structure was evident even at an excitation level where the global deformation remained in the elastic domain. Scanning Electron Microscopy (SEM) observations confirmed changes in the material microstructure at high stress concentration regions with the accumulation of fatigue cycles. Nanoindentation measurements at the regions of high stress concentration revealed an accompanying reduction in the apparent stiffness (nanoindentation stiffness) of the material. This study demonstrates the effectiveness of nonlinear vibration response to identify fatigue damage precursors in slender structures through the application of global damage detection methods.

2. Modeling development

The focus of this paper is to examine the nonlinear response of a slender isotropic cantilever beam exposed to harmonic rotation base excitation near its fundamental frequency and the influence of fatigue cycles. The authors studied a cantilever beam with an aspect ratio of 8 (AR=length/width); a detailed discussion is provided in Section 3. The experimental results demonstrated progressive structural softening due to forward-stepped harmonic rotation excitations with extended dwells near the fundamental natural frequency. An analytical model is developed using nonlinear Euler-Bernoulli beam theory with a tunable nonlinear stiffness term to account for observed changes in the global structural response due to possible degradations in the local material stiffness near the beam root (at the fixed end). In other words, the model uses a global structural parameter to capture the global structural softening response due to local changes in the material microstructure. The model also accounts for additional sources of nonlinearities, which include: inertial effects, gyroscopic stiffening and softening, high order nonlinear gyroscopic stiffening, and coupling between the rotational excitation and the corresponding local displacement.

2.1. Kinematics development

Fig. 1 illustrates the dynamics of a cantilever beam with a uniform cross-section carrying a tip mass exposed to a variable rotational base excitation. The beam is idealized as an inextensional beam; that is, stretching of the neutral axis is insignificant [27]. The beam is fixed rigidly at one end and left free at the other end (Fig. 1). Nonlinear Euler-Bernoulli theory is employed to estimate the beam tip displacement, where the effects of warping and shear deformation are neglected [14].

At the large peak response amplitudes, the nonlinear terms in the equations of motion become as important as the linear ones. The beam length-to-width ratio is long enough to cause significant nonlinear flexural deformation but is short enough to assume that the beam undergoes purely planar flexural vibrations as long as the tip mass and cross-section geometry are symmetric with respect to the beam centerline [5]. The first flexural mode is approximated to be the same as the mode shape generated from

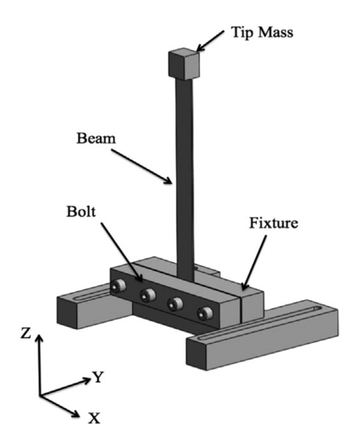

Fig. 1. Slender beam with tip mass attached to a rigid fixture.